MQW nanomembrane assemblies for visible light communications

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Abstract: We report color-conversion of InGaN LEDs and lasers using an AlInGaP multi-quantum-well nanomembrane. In particular, we demonstrate free-space OOK data transmission at 180 Mb/s from a laser diode blue-to-red converted by a heterogeneous nanomembrane/sapphire lens assembly.

Introduction: InGaN optoelectronics can be combined with efficient down-converting materials for applications in LED- and laser-based lighting and illumination [1-3]. The concept can be extended to visible light communications (VLC), which uses solid-state visible sources to transmit data, with the added requirement of a short excited-state lifetime for the color-converting material so that sources can be modulated at high speed [4 – 6]. In this work, we report color-conversion of 450nm micro-LEDs and of a 450nm laser diode (LD) with structures based on an AlInGaP inorganic MQW nanomembrane (NM). One advantage of the inorganic NM over alternative color-converters is its photo- and thermal stability. The thermal performance of the NM can be increased by judicious heterogeneous integration with other materials, *e.g.* sapphire or diamond, which can further be shaped to improve extraction efficiency. This capability makes inorganic NMs ideal candidates for color conversion of high power light sources. In the following, we describe the fabrication of the NM color-converting structure and devices. We then discuss the experimental characterization of a corresponding hybrid LED and of a remote color-converter for the LD. We also report on the initial demonstration of free-space OOK data transmission of the latter.

Fabrication: The color-converter MQW region was grown by molecular beam epitaxy on a GaAs substrate. It has a total of 6 InGaP/AlInGaP quantum wells distributed in pairs over a $5\lambda/2$ sub-cavity enclosed by two 10nm InGaP capping layers. This structure is designed to absorb more than 90% at 450 nm and for re-emission in the red at 650 nm but other wavelengths are possible by modifying the design. After processing, the membranes have typically a surface area of a few mm^2 and are several hundred nanometers thick, which helps ensure efficient Van der Waals bonding and assembly of multi-element structures as described below. For processing, the MQW structure is first fixed onto a temporary glass holder using DI-water for adherence and then exposed to selective chemical etching to remove the GaAs substrate. After the membrane is separated from the temporary glass substrate by floating in water, it is, for the hybrid LED, bonded by capillarity onto the sapphire window (polished epi-substrate) of the micro-LED array (Fig 1a). A sapphire or diamond lens, with a hemispherical diameter of 2 mm and 4 mm and focal length of 0.5 mm and 4 mm respectively, is subsequently bonded on top to improve light extraction (Fig 1.b). The micro-LED array used for the fully hybridized LED (Fig 1b) was designed in a flip-chip format with individually addressable 450nm-emitting square pixels ranging from 150 µm x 150 µm down to 50 µm x 50 µm in size. The full LED device fabrication follows the same processes as described in [7]. For the remote LD pumping samples, the membrane is simply bonded to the sapphire or diamond lens after the floating step. An optional dielectric mirror can be added.

Experimental results: All samples were studied in terms of L-I-V and modulation bandwidth responses. Different pixel sizes were measured in the case of the hybrid LED. The converted optical power from the NM depends on the size of the pixel (Fig 1c). A typical hybrid micro-LED of 150 µm x 150 µm has a maximum optical power of 0.12 mW with peak emission at 650 nm. This is currently limited by thermal rollover as there is no heat-sinking implemented, but the sapphire lens already helps to spread the heat. It was found that the color-converter's extracted power efficiency when using a diamond or sapphire lens was 0.96 ± 0.23%. The electrical-to-optical bandwidth of the hybrid LED was up to 65 MHz, the intrinsic

NM bandwidth being 130 MHz. The extracted power can be further increased by adding a high-reflectivity mirror on one side of the NM, as was done for one of the LD-pumped samples. In this case the color-converter's efficiency was 1.14 ± 0.26% compared to 0.42 ± 0.02% with no mirror. Data transmission was carried out under remote LD pumping on a converter with no mirror. The DC signal was combined with the RF one, in a 2^7-1 PRBS OOK scheme, using a Bias-Tee. Error-free data at 180 Mb/s for a BER of 10^{-9} was obtained (Fig 2b). With improvements in the LD driving conditions and the use of high level encoding schemes such OFDM we expect to be able to push the data rate to Gb/s levels.

Conclusion: We report nanomembrane-based fast-response color conversion and prove that the concept is attractive for VLC with, in principle, wavelength coverage across the visible spectrum possible with III-V AlGaInP (yellow to red), InGaN (green) and II-VI CdMgZnSe (green to orange) [8, 9] epitaxial alloys. We have shown a fully integrated hybrid LED and demonstrated OOK error-free transmission at 180 Mb/s (BER of 10^{-9}) for a LD-pumped NM. Finally, we note that the NM geometry is attractive for controlled nano-assembly using transfer-printing [10] and recent advances on the printing of AlInGaP NMs for color conversion applications will also be presented

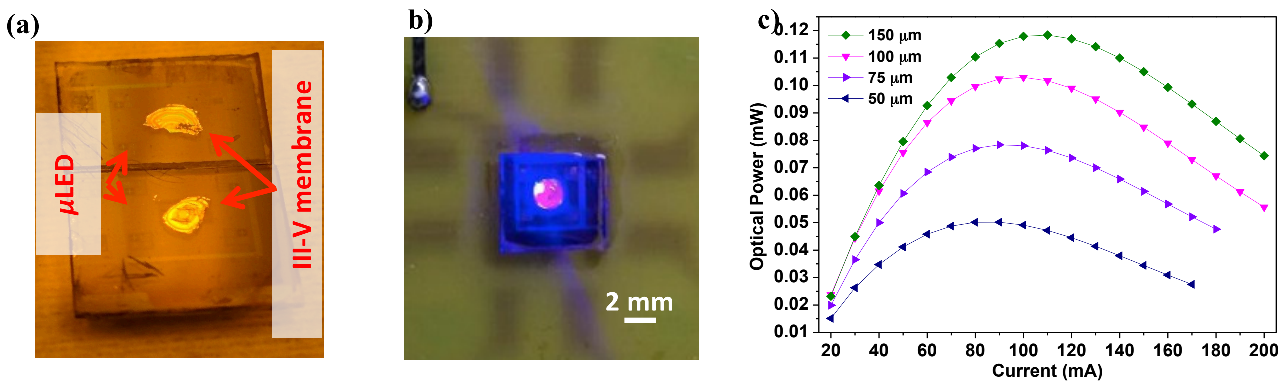

Figure 1: a) Two micro-LED chips with capillary-bonded AlInGaP membranes, b) Hybrid LED with integrated sapphire lens under operation and c) Hybrid LED L-I curve for different micro-LED pixel sizes.

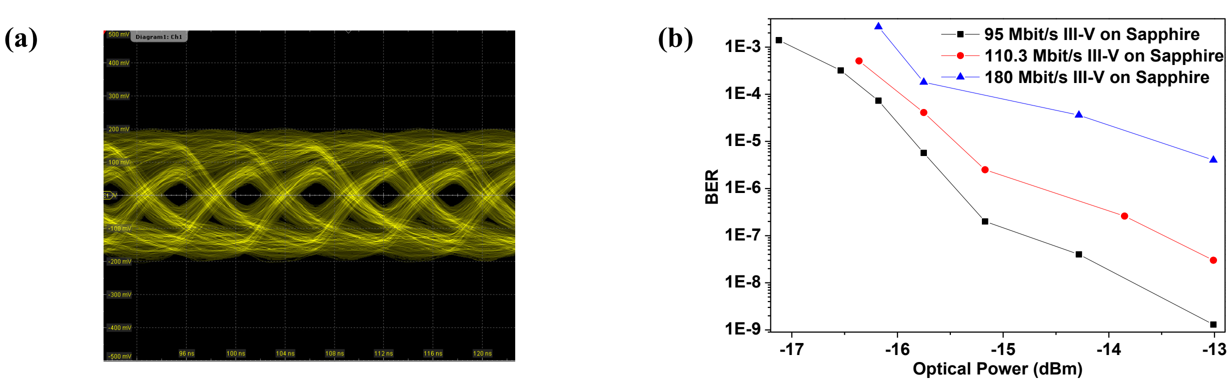

Figure 2: a) Eye-diagram at 180Mbits/s, b) OOK modulation BER for the NM/sapphire lens structure.

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